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ELEMENTARY PRINCIPLES OF NUCLEAR POWER

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CITY PLANNING DIVISION

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This paper is one of a group given at Lehigh University and Lafayette College at Bethlehem and Easton, Pa., on October 22, 1954, at a special program of the City Planning Division in conjunction with the Lehigh Valley Section. It was designed to bring out the relationship between future commercial applications of the use of atomic fuel for developing power and city and regional planning.

The following papers comprise the program: "Elementary Principles of Nuclear Power" by John W. Landis, Customer Relations, Atomic Energy Div., The Babcock and Wilcox Co., New York, N. Y.,; "Prospects for Use of Nuclear Power" by H. W. Huntley, Member, Atomic Power Study, General Electric Co., Schenectady, N. Y.; "Impact of Atomic Development on Growth and Planning of Urban Regions" by Park H. Martin, M. ASCE, Executive Director, Allegheny Conference on Community Development, Pittsburgh, Pa.; "Environmental Considerations in the Development of the Atomic Energy Industry" by Arthur E. Gorman, M. ASCE, Sanitary Engineer, U. S. Atomic Energy Commission, Washington, D. C.; and "Local Government in the Atomic Age" by Harold A. Alderfer, Prof. of Political Science, Penn State Univ., State College, Pa.

These papers presented, first, the methods by which nuclear energy could be converted into power, reviewed the prospects for such power, and then took up: the effect that such atomic plants and the power which they would create might have on the future planning of metropolitan areas, the ways in which the public health might be protected against any harmful wastes, and, finally, the revisions in governmental structure that might be desirable as a result of the atomic age.

They pointed out that careful consideration should be given to site selection, both in consideration of adjoining developments and to assure safe disposal of radioactive wastes. Assurance was given that safe designs are within the realm of sound engineering. At the same time, it was pointed out that the potential new industry presents a challenge not only to engineers but to other scientists, private management, and public officials involved.

ELEMENTARY PRINCIPLES OF NUCLEAR POWER[1]

John W. Landis[2]

SUMMARY

This paper is a consideration of the principles of nuclear reactor theory and construction. It begins with a discussion of the neutron, the key to the operation of nuclear devices, and goes on to explain the concepts and processes which are basic to nuclear reactor design. It describes the various reactor components such as the fuel, moderator, coolant, control system, structural elements, reflector, and shield. It points out certain major problems encountered in design and operation and tells how each problem is being approached and what possibilities there are for solution.

Also included are lists of advantages and disadvantages of the general types of reactors and brief descriptions and illustrations of specific reactors and their components, as well as figures showing a schematic chain reaction and the effects of radiation on a sample fuel piece.

The recent history of atomic energy could very well be subtitled "The Story of the Neutron." This elementary particle, discovered only as long ago as 1932, is the key to the operation of the nuclear devices which we propose to utilize in the generation of what is commonly termed "nuclear power."

The neutron is one of the two basic building blocks of matter. The other is the proton. Each of these particles is approximately 1840 times as massive as the electron but they differ from one another when it comes to electric charge. The proton carries a unit positive charge (equal but opposite to the charge of the electron) while the neutron has no charge at all. These two particles in various combinations make up all the nuclei known to man.

It is because of its lack of charge that the neutron is so useful in the field of nuclear power. In fact, its neutral character is entirely responsible for the field of nuclear power.

Since it has no charge the neutron is able to penetrate matter very easily. It isn't repelled or affected by the ordinary Coulomb forces. It can sneak into and through a block of solid material as readily as a bird goes through the bars of an elephant's cage. What's more, if it collides with a nucleus directly it may penetrate the nucleus itself. This is the case in what is known as "nuclear fission."

In nuclear fission the neutron invades the so-called <u>fissionable</u> nucleus, disrupts the nuclear forces which hold it together and causes it to split apart. Fission is just the physicist's term for splitting apart or breaking up.

Three types of fissionable nuclei are available to man today in appreciable

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1. For the meeting of City Planning Division, American Society of Civil Engineers, Lehigh University and Lafayette College, October 22, 1954.
2. The Babcock & Wilcox Co., New York, N. Y.

quantities. They are uranium-235, uranium-233 and plutonium-239. The number after the element's name in each case denotes the atomic weight of the particular isotope involved. Isotopes are merely variations of the same element having different atomic weights. These variations have the same chemical characteristics.

U-235 occurs naturally. It comprises .71% of natural uranium. Pu-239 and U-233 are secondary fissionable materials, i.e., they are made by transmutation of naturally occurring isotopes—U-238 to the former and thorium-232 to the latter. Each of these transmutations is neutron-induced and can be carried out in conjunction with a fission chain reaction (see below) if there are enough neutrons available. This gives rise to the possibility of breeding—producing as much or more fuel as is consumed—which will be discussed at more length later.

U-238 and thorium-232 are known as fertile materials. U-238 comprises 99.3% of natural uranium. Natural thorium is practically pure thorium-232. Natural uranium can be enriched in U-235 content by the process known as "gaseous diffusion." This is carried out in the great government-owned plants at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio.

The mechanism of the type of fission I am talking about differs somewhat from the fission which may occur as a result of nuclear bombardment. In the type with which we are concerned, the neutron is absorbed or swallowed by the target nucleus; its kinetic energy does not contribute to the reaction. Furthermore, the products include not only heavy fragments (two) but also two or three or more neutrons. This gives rise to the possibility of a chain reaction—that is, the neutrons emitted might be utilized to incite the next fission.

This is exactly what occurs in the atom bomb and, in the peaceful realm, in the so-called "nuclear reactor." The bomb is designed to cause an extremely fast and completely self-consuming divergent chain reaction. The reactor is limited to a slower evolution of heat and cannot explode. If U-235 is used as fuel, an average of 2.5 neutrons is given off by each fission. If Pu-239 is used, an average of 3.0 neutrons is given off. Only one neutron is required to continue the chain reaction; the remainder therefore are available to cover losses, and to convert fertile material to fissionable material, to be used for experimental purposes, or to produce radioisotopes. A constant rate of heat production is obtained by establishing and maintaining a balance between neutron production and neutron absorption and losses. This balance is made possible largely because a fraction of the neutrons emitted by fission are "delayed," thus giving mechanical and electronic devices enough time to control the reaction by varying the amount of neutron-absorbing materials present.

Figure 1 shows the successive stages of a fission chain reaction with U-235 in a thermal reactor. Three neutrons are depicted instead of 2.5 for convenience.

The nuclear physicist expresses the reactions shown in this diagram as follows:

$$\text{U-235} + n \xrightarrow{\text{FISSION}} \text{FISSION PRODUCTS} + 2.5\,n + \gamma\text{'S} + \text{HEAT}$$

$$\text{U-238} + n \longrightarrow \text{U-239} + \gamma$$

$$\text{U-239} \xrightarrow{\text{23.5 MIN}} \text{Np-239} + \beta$$

$$\text{Np-239} \xrightarrow{\text{2.3 DAY}} \text{Pu-239} + \beta$$

The large amount of heat evolved by fission arises from the conversion of a small amount of mass to energy. In other words, the sum of the masses of the product particles is less than the mass of the original nucleus plus the invading neutron. The conversion ratio is expressed by Einstein's law—

Energy = Mass differential x velocity of light squared

$$(E = mc^2)$$

Since $c = 3 \times 10^{10}$cm/sec and is squared, not much mass differential is required to produce a prodigious amount of energy.

This energy manifests itself primarily in the form of kinetic energy of the relatively massive fission products. It is passed on to the general body of the fuel element by collision of the fission fragments with the other particles in the element. The fragments travel no more than one-tenth millimeter, and in giving up their energy in this short course wreak a good deal of havoc among the neighboring atoms, dislocating many from their ordinary positions in the crystalline structure and thus causing physical damage to the fuel materials.

The nuclear reactor is the heart of the new nuclear power industry. It is the device which extracts the above-mentioned fabulous amounts of heat from fissionable materials—35,000 million BTU per pound, or as much from one pound of nuclear fuel as can be obtained from 1,500 tons of coal. In the formal definition, it "initiates, maintains and controls a fission chain reaction." It takes many forms. Not only can the fuel itself be varied as to configuration, spacing, physical state, chemical composition, etc., but other materials necessarily have to be brought in: first, to improve the neutron economy of the reaction; second, to support and enclose the fuel assembly; third, to remove the heat generated; fourth, to control the reaction; and fifth, to shield the surroundings from the lethal radiation emitted.

Neutron economy is dependent on many factors, most of which are too technical to describe in detail here. Briefly, it is important to arrange the fuel and the other components in such a way that the probability of any given neutron being captured by a fissionable atom and utilized to produce fission is maximized. This means in many cases that a substance called a "moderator" must be employed in the space between the fuel elements to slow down the neutrons as they are emitted from a unit of fuel in order to increase the probability of their capture by the next unit encountered. Thus a moderator must be a material which slows down neutrons effectively and at the same time does not absorb them. The slowing-down principle is that of the billiard table: To absorb completely the energy of a particle of certain size and mass one uses a particle of similar size and mass. For example, all the energy of the cue ball can be imparted to any of the other balls in a direct collision. On the other hand, a ping-pong ball thrown up against one of the billiard balls would not impart much of its energy to the billiard ball. Rather it would bounce back with essentially the same energy that it had going forward. So the best "slower-downers" for neutrons are the light elements, that containing one proton in its nucleus (hydrogen) being best from the energy absorption point of view.

The second requirement for moderators, however, is the complicating factor. Most substances absorb neutrons to some degree without producing new neutrons (parasitic absorption). Because of this factor, light or ordinary water, which contains about as many hydrogen atoms per unit of volume as any other usable material, is not as effective a moderator as heavy water, which contains hydrogen atoms twice as massive as those in ordinary water.

Even graphite (pure carbon), which is 12 times the atomic mass of hydrogen, turns out to be higher on the moderator scale than ordinary water. A tabulation of the relative moderating abilities of several materials which have been widely employed is shown in Table 1.

The problem of parasitic absorption permeates reactor design. The nuclear engineer lives with it all the time. No material with a high affinity for neutrons may be used in the fuel elements (except for the fuel itself), in the structural members, in the cooling system, or in any other essential component of the reactor core, except for purposes of control. The nuclear properties of materials, therefore, are as important in this new field as the physical properties of materials are in the field of civil engineering.

Neutron economy embraces other problems, however. The core of a reactor must be designed to minimize losses through its shell. (Often a neutron reflector is employed to bounce some of the escaping neutrons back in.) It must be designed so that the neutrons do not tend to be produced in certain regions at a faster rate than in other regions. It must contain at least a "critical mass" of fissionable material.

The "critical mass" concept is one which you have probably read about. It expresses the primary characteristic of a chain-reacting system—namely, that enough fissionable material must be assembled in the particular configuration specified to permit utilization of an average of at least one neutron per fission to continue the chain reaction.

The need for structural materials in a reactor brings up a second unique problem. Many substances undergo marked physical change under intense and prolonged neutron bombardment. Since most power reactors will produce a neutron flux of at least 10^{13} neutrons per square centimeter per second (meaning that 10,000 billion neutrons pass through each square centimeter inside the reactor each second) this is a serious matter. Certain deleterious changes in ordinary materials like steel may be caused by this bombardment. Two of the most disconcerting are extreme growth along the molecular axis and loss of strength. The effect of neutron irradiation must be determined therefore for each substance to be inserted or built into a reactor core.

An example of what happens to an untreated metal rod when it is subjected to neutron bombardment is shown in Fig. 2. This illustration also shows how the neutron effect may be diminished by proper metallurgical treatment.

Figure 3 is a picture of the Materials Testing Reactor which has been operating at the National Reactor Testing Station in Idaho since 1952. In this reactor the various materials which are contemplated for use in reactor core components are tested. The MTR, as it is called, is specially designed to permit insertion of a new sample or equipment in the proper neutron flux region without affecting too greatly the irradiation of the samples or equipments already in situ.

The major nuclear fragments resulting from the process of fission are often highly radioactive. (The fragments may be any of the many intermediate nuclei.) Therefore great care must be taken to prevent their release to the atmosphere or ground waters or solid matter in and around the reactor structure. This is done in most cases by confining the particles to the fuel elements in which they originate, and the most common method of confinement is cladding the fuel elements with an impervious coat of a suitable metal. This coat must be absolutely leak-proof, must not absorb neutrons to a significant degree, must have a high heat conductivity, must be machined to very close tolerance, must resist corrosion by the coolant, must not suffer radiation damage, must be compatible with the fuel, and should be relatively inexpensive, but otherwise this is not much of a problem as reactor design problems

go. I mention it at this point because it ties in with both the structural materials and the coolant materials which must be introduced, the second and third items of our list.

Selection of the proper coolant is often the first problem that faces the reactor engineer when he designs a reactor for a particular application. If he wants high temperature and low pressure, he must utilize a liquid metal. If he can stand relatively low temperature and perhaps very high pressure, he may decide on water, heavy water, or another low boiling liquid. If he desires to set up a combination of high temperature and high pressure he may use carbon dioxide or helium. Whatever his choice, as before, it must be a low neutron absorbing material and one which does not decompose or change its thermal properties or flow characteristics under neutron bombardment.

Advantages of the liquid metal coolants, in addition to permitting high-temperature operation without pressurization, are that they possess high heat conductivities and do not decompose. Advantages of ordinary water, for example, on the other hand, are that it is cheap, has high heat capacity, requires only ordinary pumps and conduits, does not become radioactive, does not react violently with other reactor components except perhaps aluminum, and is a substance whose properties and effects are well known.

A liquid metal cooled power reactor system is shown in Fig. 4.

Going on to the fourth and fifth categories of materials which must be used in a reactor assembly—control devices and shielding—you will note new and different problems.

Slight excess reactivity is built into every reactor. In other words, a supercritical mass is set up. The reactor is prevented from "running away" by the control system. This usually comprises rods or plates of good neutron-absorbing materials, such as cadmium or boron, and auxiliary equipment. The latter includes dependable drives, servo-mechanisms, monitoring equipment and safety devices. As the fissionable material is loaded into the reactor, the control rods are positioned all the way in, overbalancing the excess reactivity and preventing the fission process from maintaining itself. The fission chain reaction does not start until the control rods are pulled part way out. The position of the rods determines the neutron flux density and the power level of the reactor. To maintain a required power level the rods will have to be repositioned frequently because as the fission products accumulate they "poison" the reaction, i.e., absorb neutrons. This is a sensitive operation and calls for a complex instrumentation system.

For ultimate safety, the reactor designer does not usually depend on his one or perhaps two operational control systems. He usually provides "scram" mechanisms which shut the reactor down instantaneously in the event of coolant-system failure, power failure, or some such breakdown.

The observer looking at an ordinary reactor or pile is usually impressed with its mausoleum-like aspects. It appears to be a cubic monolith with sundry tubes, shafts, pipe lines, wires, and conduits threaded through two or more faces. This massiveness is primarily due to the shield, which I have already described as an envelope protecting the surroundings from the lethal radiation emitted. For low-power reactors concrete alone will do the job. In high-power reactors, however, it may be necessary to line the concrete with iron or lead and provide a cooling system to take away the large quantities of heat generated. This liner is often referred to as the "thermal shield." In any event, sufficient mass must be built up to attenuate the radiation to a tolerable level. Each hole through the shield must be bent or baffled and properly plugged to prevent leaks.

Before proceeding with further details of reactor theory and construction, it may be well to pause for a minute at this point to define a few more terms which are commonly used in the nuclear power field.

In general a nuclear power plant differs from a conventional power plant in that a power reactor and associated special heat exchangers replace the coal handling equipment and the boiler. A power reactor is one which operates at a sufficiently high temperature to produce steam capable of turning a turbo-generator with at least moderate efficiency.

Power reactors may be classified in many ways. We have already seen how a differentiation according to the coolant used is possible. Three other major differentiations are the following:

1) Fast versus thermal
2) Heterogeneous versus homogeneous
3) Nonregenerative versus regenerative

A fast reactor utilizes the highly energetic fission neutrons directly to continue the chain reaction. A thermal reaction slows down most of these neutrons before utilizing them to continue the chain reaction. The major components of the thermal reactor are: (1) fuel, (2) moderator, (3) coolant, (4) control system, (5) structural elements, (6) reflector and (7) shield. The major components of the fast reactor are the same except that no moderator is employed but a fuel diluent may be used to create the necessary heat transfer surface. A blanket of fertile material is often employed in a breeder reactor of either type.

A homogeneous reactor is one which mixes the fuel, moderator and coolant (or just fuel and coolant in the fast type) intimately, often in liquid form. A heterogeneous reactor separates them, usually in a definite geometric arrangement.

A regenerative reactor replaces part or all of the fuel it consumes by creating new fuel from fertile material. The regenerative reactor which replaces as much as it consumes (with perhaps some excess) is known as the breeder. A non-regenerative reactor does not contribute a significant quantity of new fuel to the system in which it functions.

Some of the advantages and disadvantages of reactors in each of these classifications are the following:

List I

Fast	Thermal
Large fuel investment required	Small fuel investment required
Control problems relatively difficult	
No moderator needed	Moderator may be expensive
Fuel diluent probably needed	
High power density per unit volume	Low power density per unit volume for high-Z moderators
Circulating fuel impractical because of high concentration of fuel required	Heat removal ordinarily not difficult
Limited choice of coolants complicates heat removal	Wider choice of coolants simplifies heat removal
Large minimum critical mass	Small minimum critical mass
Separations costs may be exorbitant	

List II

Heterogeneous	Homogeneous (Fluid Fuels)
Fabrication of complex fuel shapes sometimes necessary	Fuel usually supplied in simplified, sometimes liquid form
Chemical processing involves removal of fuel elements with expensive and complicated apparatus, and special handling throughout various processing steps	Fuel may be processed continuously Selective removal of fission products and plutonium possible without handling uranium
Fission products may build up to dangerous concentrations	Fission products do not build up
No fuel-circulation corrosion problems	Corrosion and container difficulties are paramount
Radiation damage may limit burnout	Fuel may be added continuously to extend burnout
Natural uranium may be used	Enriched fuel must be used

List III

Nonregenerative	Regenerative
Useful only in certain power plants where value of fuel consumed is outweighed by unusual advantages of nuclear power	Replaces part or all of fuel consumed, but sometimes reclamation is expensive
Burnout limited to 1,000 megawatt-days/ton per cycle	Burnout is limited by products desired, but usually is greater than for non-regenerative case
Reactor core can be very small	
Limits nuclear-fuel reserves to between 1/6 and 1/7 energy content of conventional-fuel reserves	Stretches nuclear-fuel reserves up to 23 times energy content of conventional fuel reserves

To clarify how a reactor operates and to lead into a discussion of additional problems of reactor design it may be helpful to consider a simple heterogeneous thermal regenerative reactor. A reactor of this type is shown in cutaway in Fig. 5. Essentially it comprises a lattice of graphite-moderator blocks threaded horizontally with aluminum tubes containing the natural uranium fuel. Cooling is accomplished by passing air through the aluminum tubes around the slugs of uranium. Control is accomplished by means of boron steel rods riding down into the core from above. A thick concrete shield surrounds everything.

The graphite trays extending horizontally at right angles to the fuel tubes into the reactor core are holders for materials which will be converted to radioisotopes by neutron irradiation. You may have already guessed that this reactor is the now-famous "X-10" at Oak Ridge which has been producing during the past decade most of the radioisotopes which the U. S. Government is distributing for medical therapy, biological research, agricultural experimentation and other benign uses all over the world.

Returning to my discussion of reactor design problems I want to emphasize what I consider to be the three most important problems now facing the reactor designer and then give you a complete list of the problems which I have covered and others of some significance.

One of the most vexing limitations of present-day reactors is that the fuel must be removed for purification purposes after only a very small fraction of its fissionable material has been consumed. This is due to several factors chief among which are the already mentioned "poison" effect of the fission products and the radiation damage to the fuel element. Much work is in progress to achieve greater burnout of both natural and enriched fuels. This will reduce the frequency or rate of chemical processing and will necessitate fewer reactor loadings and unloadings.

The second important problem is to reduce the complexity and cost of chemical processing. Separating the fission products from the unused uranium and then extracting the plutonium produced can be the most costly item in a reactor cycle. The solvent extraction methods now commonly used require equipment that is in many instances more complex than the reactor itself, particularly since all of the operations must be carried out by remote control. Pyrometallurgical techniques give some promise of alleviating this situation. Continuous processing, of course, would be much more desirable than batch processing.

Tied in with the above is the question of fuel element fabrication. In some heterogeneous reactors this is an expensive operation. Powder metallurgical, remote-casting and die-casting methods are being investigated as possible alternatives for the intricate machine operations presently employed.

All three of these problems would be solved by the so-called "homogeneous reactor." Fuel in solution or suspension is not subject to radiation damage. Chemical processing can be made an integral part of the reactor system by bleeding off small quantities of fuel for continuous purification. Finally, fuel element fabrication is entirely eliminated. Corrosion problems of this type reactor have not been completely solved, however, and circulating large quantities of highly concentrated fuel outside the reactor appears to be impractical.

The complete list of reactor design problems which I promised you is given in Table 2. And finally, to make this a true introduction to Mr. Huntley's talk, I leave you with a list of possible power reactor types (Table 3). This is not to put Mr. Huntley on the spot but to point out to you before he begins, the magnitude of the task facing the reactor engineer who conscientiously tries to select the proper reactor for each application.

Table 1

MODERATING RATIO* FOR COMMON MODERATORS

Moderator	Slowing Down Power	Moderating Ratio
Water	1.53 cm^{-1}	72
Heavy Water	0.370	12,000
Helium	1.6×10^{-5}**	83
Beryllium	0.176	159
Carbon	0.064	170

* Moderating ratio is defined as the ratio of the slowing down power, the relative rate of absorption of the neutron energy by a unit amount of a substance, to the macroscopic neutron absorption cross-section.

** At atmospheric pressure and temperature.

Table 2

PROBLEMS OF REACTOR DEVELOPMENT

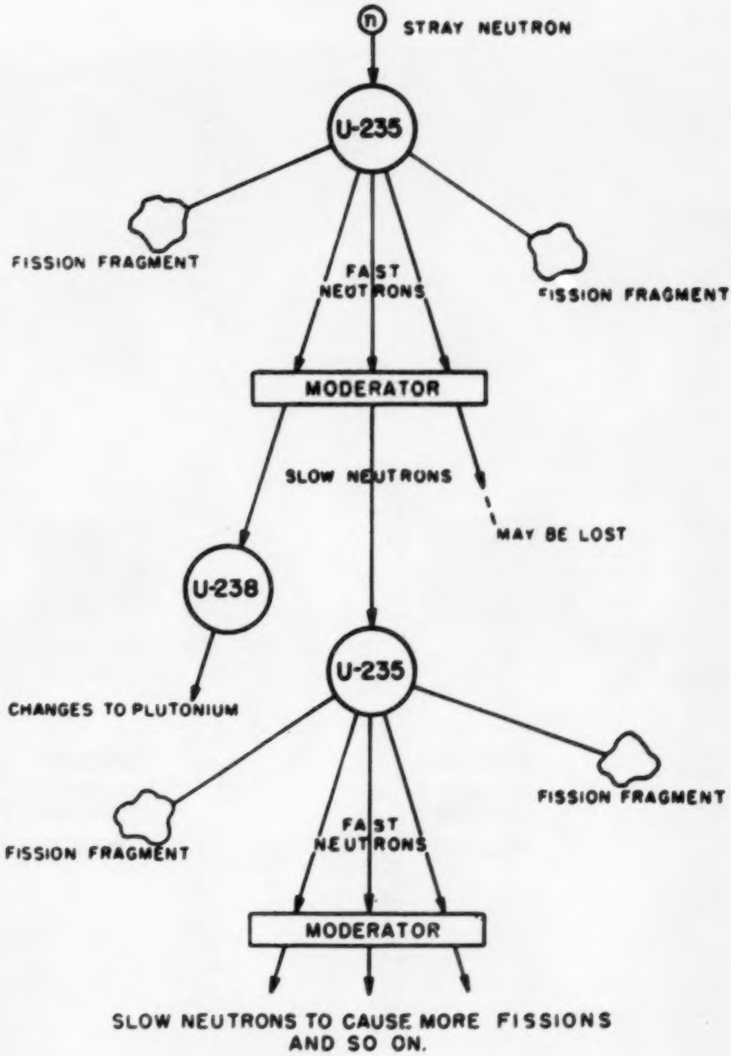
1. To achieve greater burnout of both natural and enriched fuels, thus reducing the frequency of rate of chemical processing.
2. To reduce the complexity and cost of chemical processing.
3. To reduce or eliminate expensive fuel-element fabrication.
4. To compare carefully the fuel costs of breeders with the fuel costs of converters.
5. To eliminate external heat exchange by boiling in the reactor core.
6. To attain high specific power.
7. To reduce corrosion caused by coolants and/or liquid fuels.
8. To apply supercritical water technology.
9. To design inexpensive leak-proof equipment to handle liquid metal coolants.
10. To improve methods of breeding, both internal and external.
11. To work out better control devices especially for fast reactors.
12. To develop materials of construction which do not absorb neutrons parasitically, and which can withstand high temperatures and intense and prolonged neutron bombardment.
13. To uncover new useful coolants.
14. To reduce the costs of special materials such as zirconium, beryllium, heavy water, titanium, etc.
15. To simplify construction generally.
16. To develop methods of handling and disposing of radioactive wastes which will minimize health hazards.
17. To fabricate better shields at lower costs.

Table 3

TYPES OF POSSIBLE POWER REACTORS

1. Light water moderated and cooled, slightly or highly enriched uranium
2. Heavy water moderated, light water cooled, natural or slightly enriched uranium
3. Heavy water moderated and cooled, natural or slightly enriched uranium
4. Boiling light water, slightly or highly enriched uranium
5. Boiling heavy water, natural or slightly enriched uranium
6. Aqueous homogeneous (light water), highly enriched uranium
7. Aqueous homogeneous (heavy water), moderately or highly enriched uranium
8. Liquid metal fuel (uranium-bismuth solution), graphite moderated, highly enriched uranium
9. Cast fuel (U-235 or plutonium) sodium cooled fast breeder
10. Liquid metal fuel fast breeder
11. Graphite moderated, sodium cooled, slightly enriched uranium
12. Graphite moderated, light water cooled, slightly enriched uranium

FIGURE 1



SCHEMATIC DIAGRAM OF FISSION CHAIN REACTION USING A MODERATOR TO SLOW NEUTRONS TO SPEEDS MORE LIKELY TO CAUSE FISSION

FIGURE 2

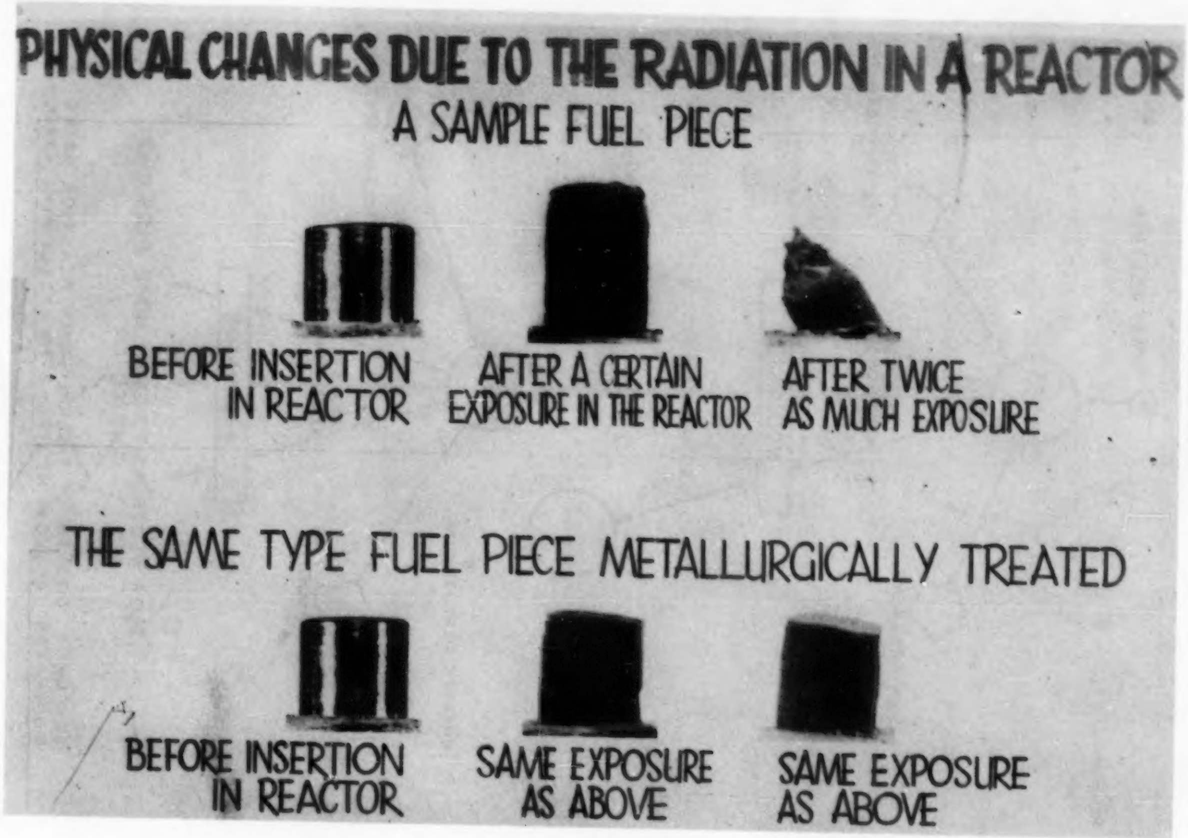

PHYSICAL CHANGES DUE TO THE RADIATION IN A REACTOR
A SAMPLE FUEL PIECE
BEFORE INSERTION IN REACTOR
AFTER A CERTAIN EXPOSURE IN THE REACTOR
AFTER TWICE AS MUCH EXPOSURE
THE SAME TYPE FUEL PIECE METALLURGICALLY TREATED
BEFORE INSERTION IN REACTOR
SAME EXPOSURE AS ABOVE
SAME EXPOSURE AS ABOVE

FIGURE 3

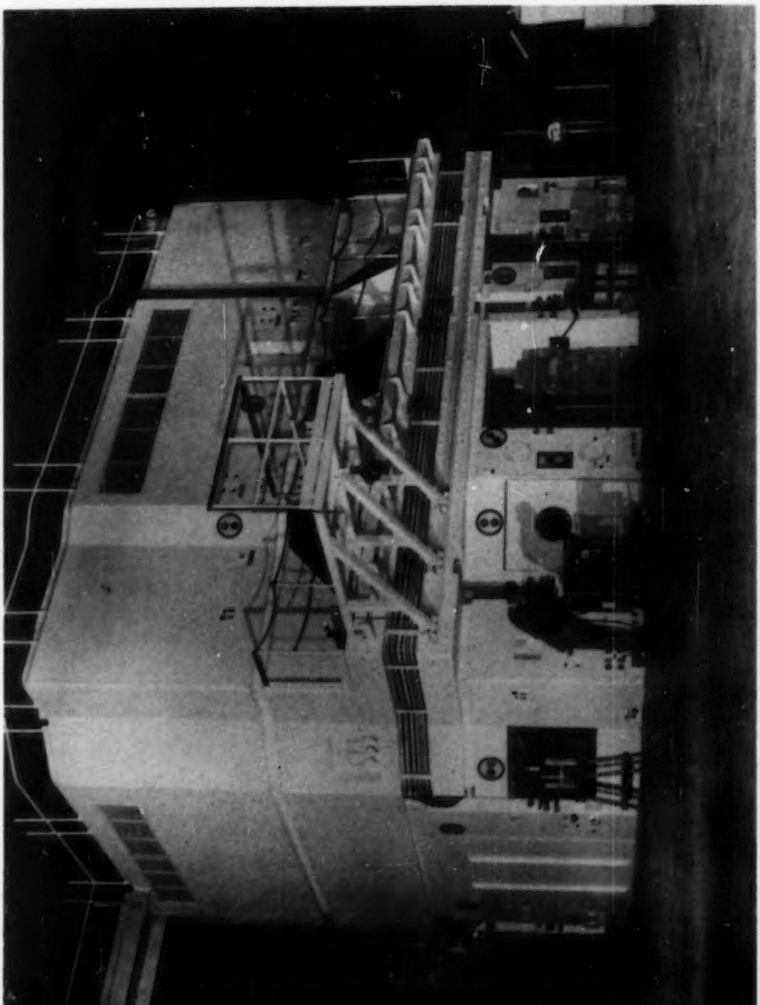
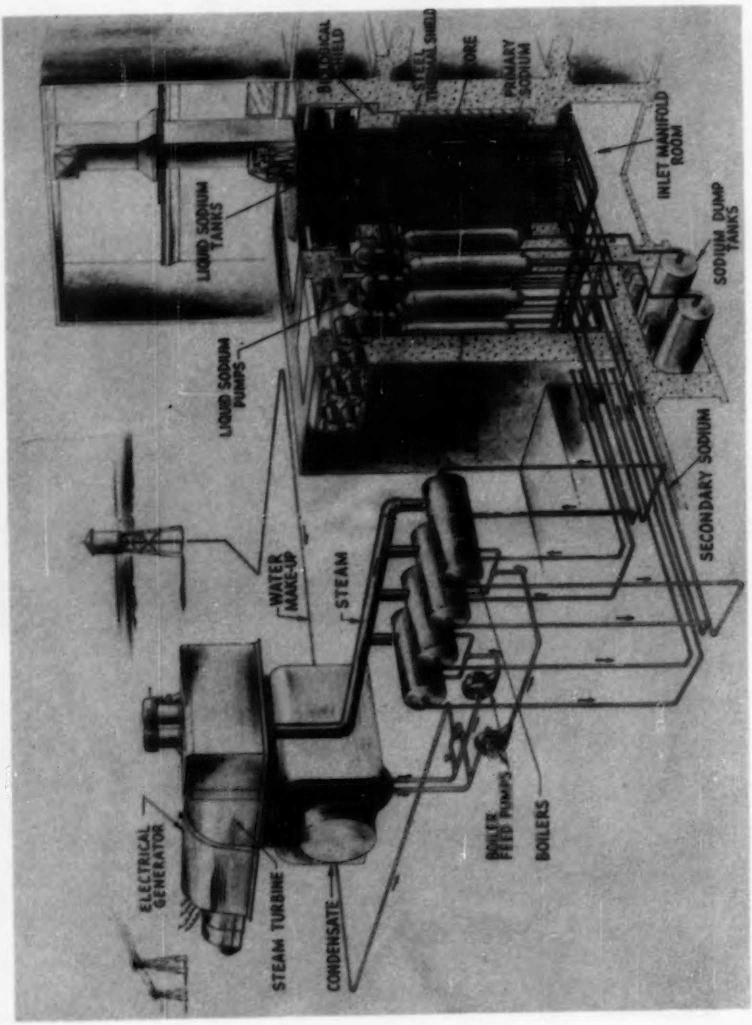
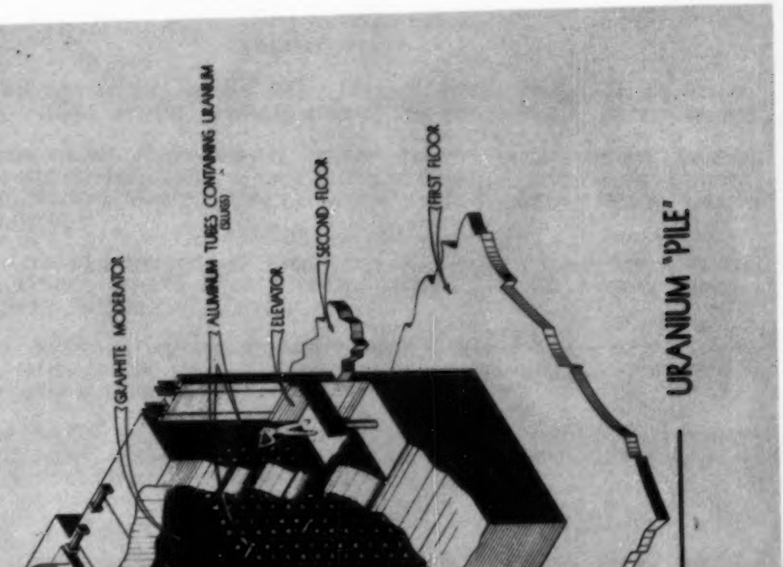


FIGURE 4



ELECTRICAL GENERATOR
STEAM TURBINE
CONDENSATE
WATER MAKE-UP
STEAM
BOILER FEED PUMPS
BOILERS
LIQUID SODIUM PUMPS
LIQUID SODIUM TANKS
BIOLOGICAL SHIELD
STEEL THERMAL SHIELD
CORE
PRIMARY SODIUM
INLET MANIFOLD ROOM
SODIUM DUMP TANKS
SECONDARY SODIUM

FIGURE 5



NUCLEAR REACTOR — URANIUM "PILE"

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AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

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DECEMBER: 558(ST), 559(ST), 560(ST), 561(ST), 562(ST), 563(ST)[c], 564(HY), 565(HY), 566(HY), 567(HY), 568(HY)[c], 569(SM), 570(SM), 571(SM), 572(SM)[c], 573(SM)[c], 574(SU), 575(SU), 576(SU), 577(SU), 578(HY), 579(ST), 580(SU), 581(SU), 582(Index).

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JANUARY: 583(ST), 584(ST), 585(ST), 586(ST), 587(ST), 588(ST), 589(ST)[c], 590(SA), 591(SA), 592(SA), 593(SA), 594(SA), 595(SA)[c], 596(HW), 597(HW), 598(HW)[c], 599(CP), 600(CP), 601(CP), 602(CP), 603(CP), 604(EM), 605(EM), 606(EM)[c], 607(EM).

FEBRUARY: 608(WW), 609(WW), 610(WW), 611(WW), 612(WW), 613(WW), 614(WW), 615(WW), 616(WW), 617(IR), 618(IR), 619(IR), 620(IR), 621(IR)[c], 622(IR), 623(IR), 624(HY)[c], 625(HY), 626(HY), 627(HY), 628(HY), 629(HY), 630(HY), 631(HY), 632(CO), 633(CO).

MARCH: 634(PO), 635(PO), 636(PO), 637(PO), 638(PO), 639(PO), 640(PO), 641(PO)[c], 642(SA), 643(SA), 644(SA), 645(SA), 646(SA), 647(SA)[c], 648(ST), 649(ST), 650(ST), 651(ST), 652(ST), 653(ST), 654(ST)[c], 655(SA), 656(SM)[c], 657(SM)[c], 658(SM)[c].

APRIL: 659(ST), 660(ST), 661(ST)[c], 662(ST), 663(ST), 664(ST)[c], 665(HY)[c], 666(HY), 667(HY), 668(HY), 669(HY), 670(EM), 671(EM), 672(EM), 673(EM), 674(EM), 675(EM), 676(EM), 677(EM), 678(HY).

MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

JUNE: 702(HW), 703(HW), 704(HW)[c], 705(IR), 706(IR), 707(IR), 708(IR), 709(HY)[c], 710(CP), 711(CP), 712(CP), 713(CP)[c], 714(HY), 715(HY), 716(HY), 717(HY), 718(SM)[c], 719(HY)[c], 720(AT), 721(AT), 722(SU), 723(WW), 724(WW), 725(WW), 726(WW)[c], 727(WW), 728(IR), 729(IR), 730(SU)[c], 731(SU).

JULY: 732(ST), 733(ST), 734(ST), 735(ST), 736(ST), 737(PO), 738(PO), 739(PO), 740(PO), 741(PO), 742(PO), 743(HY), 744(HY), 745(HY), 746(HY), 747(HY), 748(HY)[c], 749(SA), 750(SA), 751(SA), 752(SA)[c], 753(SM), 754(SM), 755(SM), 756(SM), 757(SM), 758(CO)[c], 759(SM)[c], 760(WW)[c].

AUGUST: 761(BD), 762(ST), 763(ST), 764(ST), 765(ST)[c], 766(CP), 767(CP), 768(CP), 769(CP), 770(CP), 771(EM), 772(EM), 773(SA), 774(EM), 775(EM), 776(EM)[c], 777(AT), 778(AT), 779(SA), 780(SA), 781(SA), 782(SA)[c], 783(HW), 784(HW), 785(CP), 786(ST).

c. Discussion of several papers, grouped by Divisions.